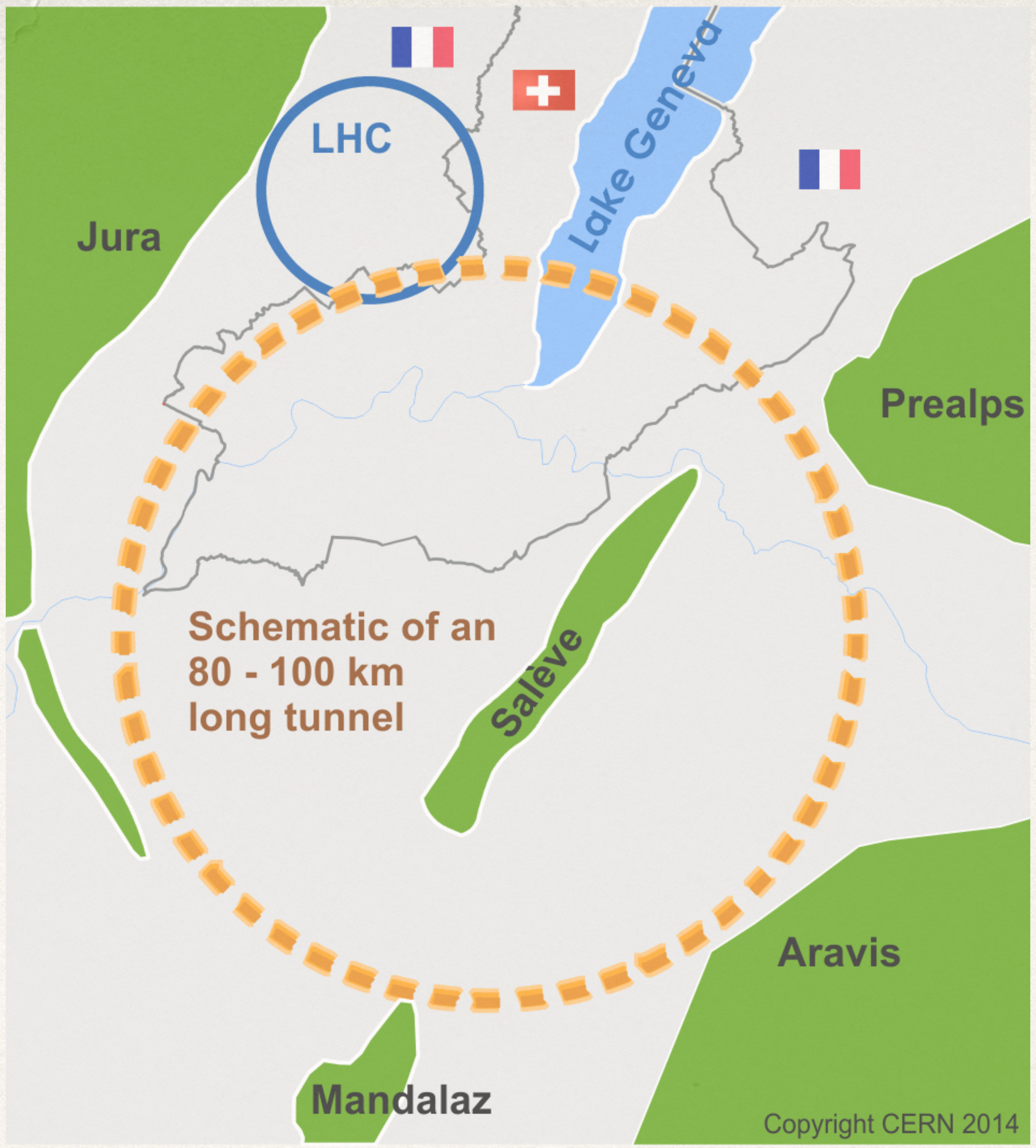
FCC-ee

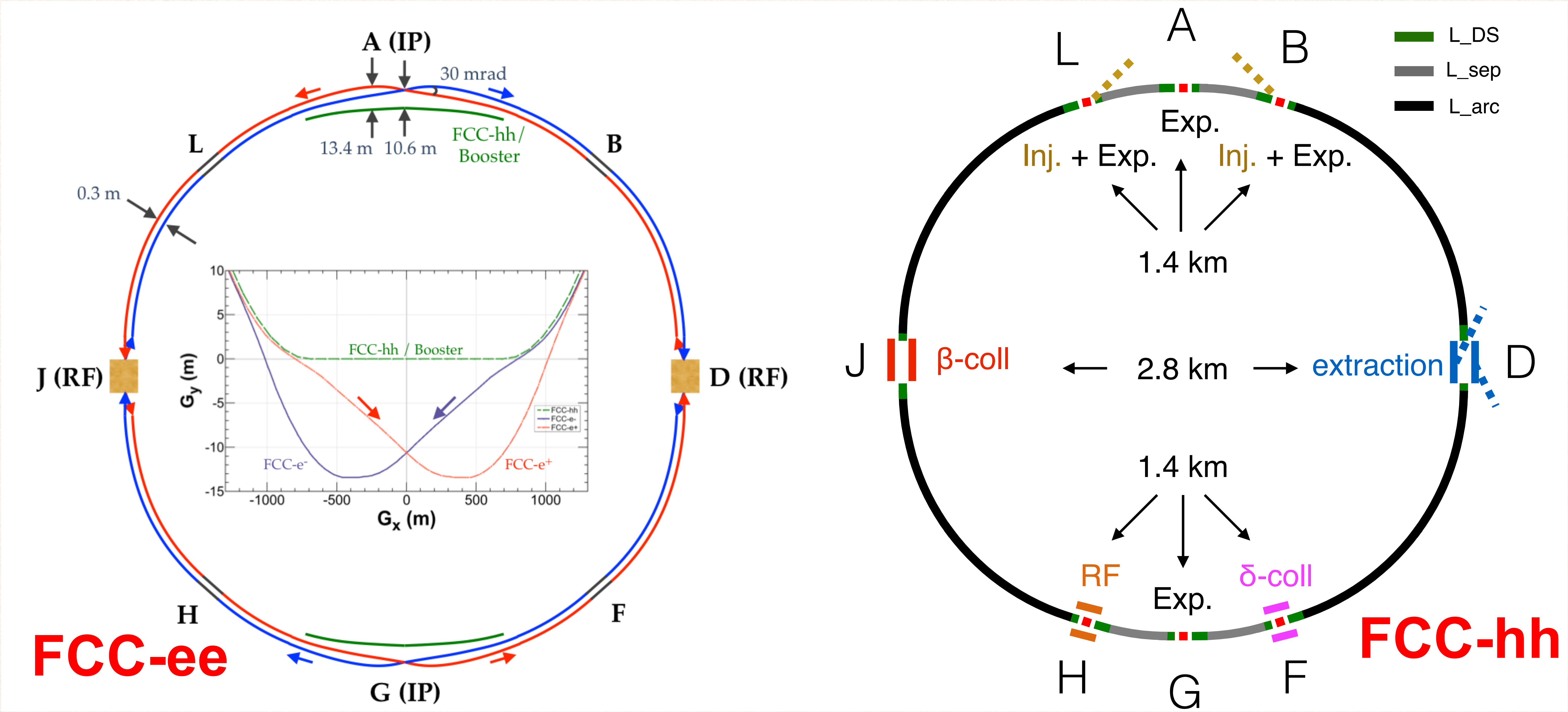


K. Oide (CERN, KEK)

Many thanks to M. Benedikt, A. Blondel, E. Jensen, D. Tommasini, J. Wenninger, F. Zimmermann, and all FCC-ee collaborators.

FCC-ee

- FCC-ee is an electron-positron circular collider sharing a common tunnel with the subsequent FCC-hh hadron collider.



- The beam energy ranges from 45.6 to 182.5 GeV covering at least four operation points for Z-pole, $W^{\pm}$, ZH, and $t\bar{t}$ productions.

Future Circular Collider Study. Volume 2: The Lepton Collider (FCC-ee) Conceptual Design Report, preprint edited by M. Benedikt et al. CERN accelerator reports, CERN-ACC-2018-0057, Geneva, December 2018. Published in Eur. Phys. J. ST.

Physics Briefing Book : Input for the European Strategy for Particle Physics Update 2020, arXiv:1910.11775 ; CERN-ESU-004

FCC-ee: Brief description

- Physics reach
  - Broad & unique physics program with $5x10^{12}$ Z, 10^8 WW, 10^6 ZH and 10^6 $t\bar{t}$.
  - Discovery potential via precision measurements, sensitivity to new phenomena & observation of feebly coupled particles.
  - Fundamental synergy and complementarity with the FCC-hh, 100 TeV hadron collider.
  - Differences and complementarity with linear colliders.

- Main systems:
  - Double-ring collider with 2 interaction points (IP) & a booster synchrotron in a ~100 km tunnel common with the FCC-hh hadron collider.
  - An injector complex consisting of a linac, a pre-booster ring, e^+ source with a damping ring to ensure the top-up injection.

FCC-ee: Brief description (cont'd)

- Key technologies and maturity
  - Based on existing, verified technologies on e^+e^- circular colliders for RF, magnets, vacuum, instrumentations, control, injectors, etc.
  - Technologies are basically mature, but need engineering finalizations on components such as NbCu cavities, high-efficiency RF sources, machine-detector interface, instrumentations, e^+ source, etc.

- Key beam physics challenges
  - Beamstrahlung-dominated collision: ensure charge imbalance between e^+e^- within ±3-±5% for each bunch.
  - Precise machine handling to preserve the emittance, beam optics, polarized pilot bunches, and the local energy at collision.

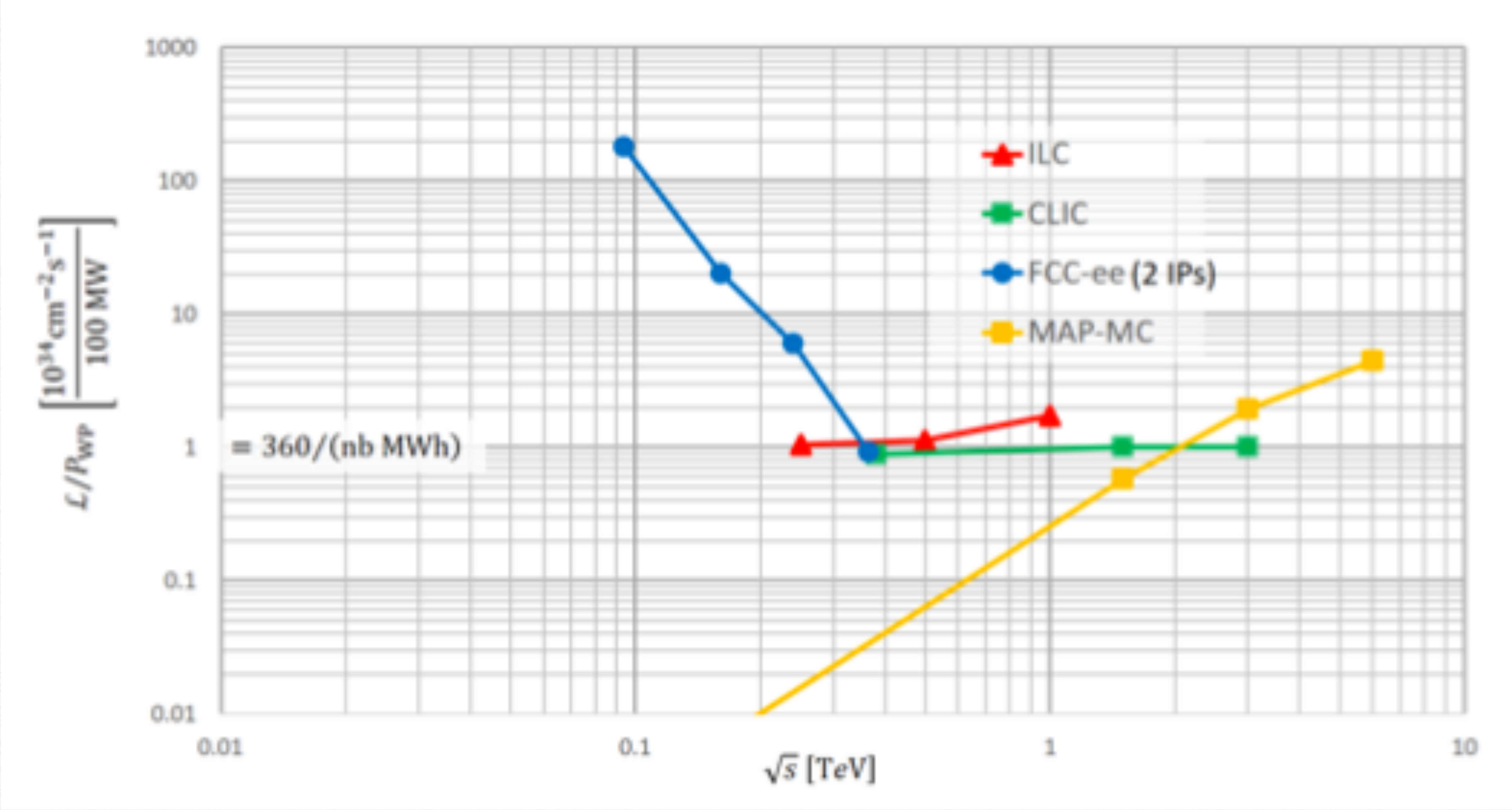
- Timeline (see slide 9):
  - ~8 years for accelerator & detector engineering finalization until permissions.
  - ~7 years for tunnel & civil construction, overlapping with ~8 years for installation and commissioning, ~10 years in total after permissions.
  - A break for a year before $t\bar{t}$ to install additional RF systems.
  - Engineering finalization & prototyping will be performed in parallel with above.
  - Complete matching with the HL-LHC run plan.

Facility "Standard Table"

FCC-ee / K. Oide	e^+e^-	katsunobu.oide@cern.ch			
Beam Energy, range	GeV	45.6, ±2	80, ±2	120, -10+5	182.5, -12+2
Peak Luminosity (10^34)	cm-2 s-1	460 / 2IP	56 / 2IP	17 / 2IP	3.1 / 2IP
Int. Luminosity	ab-1/yr	48 / 2IP	6 / 2IP	1.7 / 2IP	0.34 / 2IP
Beam dE/E at IP		3.8×10^{-6}	10×10^{-6}	26×10^{-6}	73×10^{-6}
Transv. Beam sizes at IP x/y	um	6.4 / 0.028	13.0 / 0.041	13.7 / 0.036	38.2 / 0.068
Rms bunch length /length of interaction area/ beta*	cm	1.21/0.042/0.08	0.60/0.085/0.1	0.53/0.09/0.1	0.25/0.18/0.16
Crossing angle	urad	±15000			
Rep./Rev. frequency	Hz	3066.7			
Bunch spacing	ns	17.5	160	990	3400
# of IPs		2			
# of bunches		16640 / ring	2000 / ring	328 / ring	48 / ring
Length/Circumference	km	97.756			
Facility site power	MW	259	277	282	340
Cost range	$B US	10.5 (BCHF)			+1.1 (BCHF)
Timescale till operations	yr	19	+4	+2	+4

FCC-ee: Main advantages

- The highest luminosity / wall-plug power at each energy from Z (45.6 GeV) to $t\bar{t}$(182.5 GeV).



Physics Briefing Book

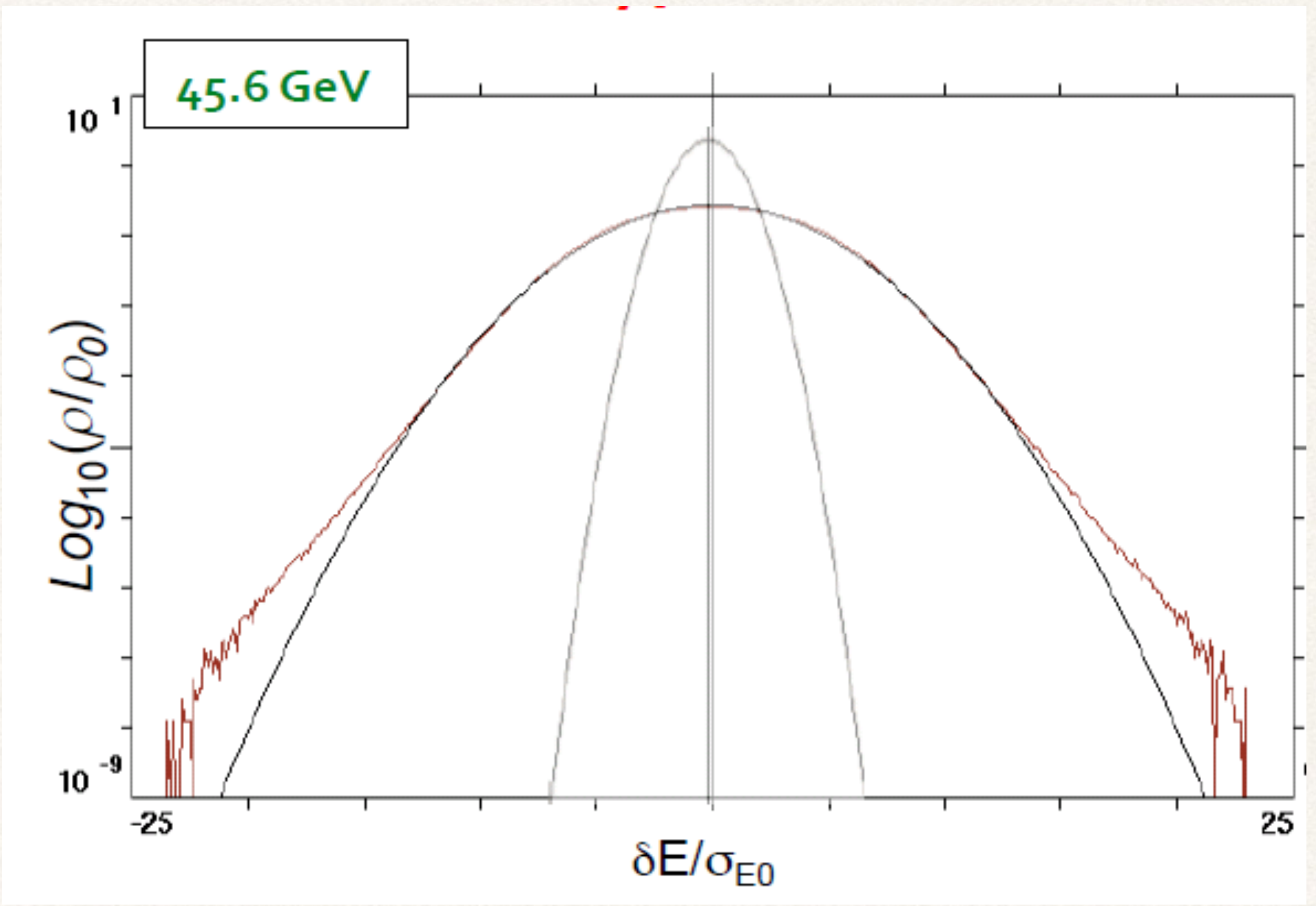
- Based on the experienced scheme and technology of e^+e^- colliders, all around the world since 1960's, including DORIS, SPEAR, VEPP, PETRA, PEP, TRISTAN, SLC, LEP, PEP-II, KEKB, BEPC, DAFNE, SuperKEKB…
- Predictable, reliable performance with few unknowns.
- Top-up injection, as proved in PEP-II and KEKB, keeps luminosity constant all the time.
- Very high precision experiments with continuous center-of-mass energy calibration using spin resonance, esp. at Z &$W^{\pm}$.

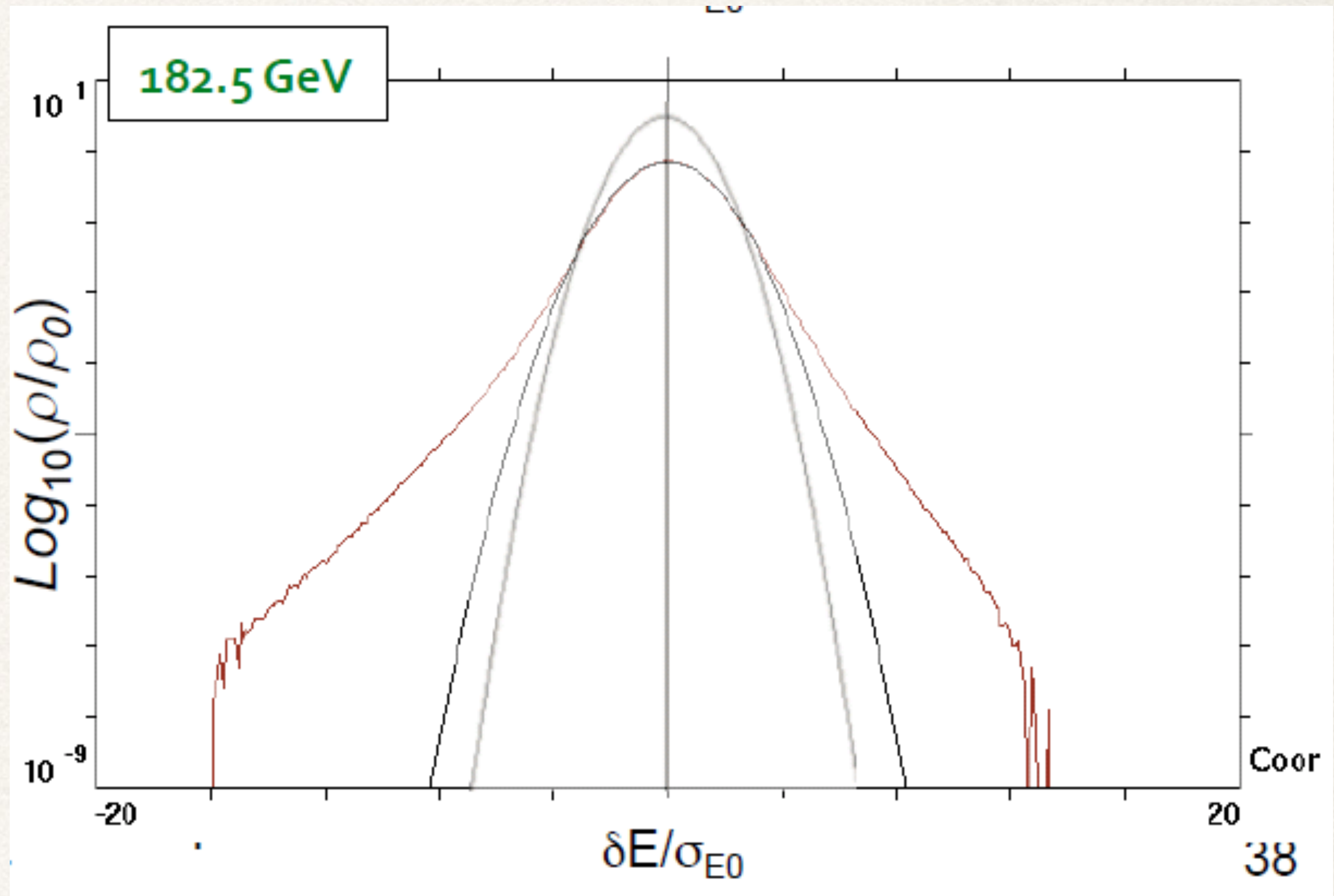
FCC-ee: Potentials for upgrades

- The highest collision **energy** is basically limited by the synchrotron radiation (SR) loss. The compensation of the SR loss requires huge acceleration, which does not fit into the tunnel. Nevertheless the stored current, thus the **luminosity** is reduced for higher energy with a fixed SR power.
    - This condition can be relaxed by an energy-recovery linac (ERL) option.
- The s-channel Higgs production at $E_{\mathrm{beam}} = 62.5\,\mathrm{GeV}$ with an energy-spread reduction scheme is a conceivable upgrade under study.
- The total **luminosity** can be 1.7 times higher by 4 IP option.
    - The additional costs for caverns and tunnels are the main obstacle.

FCC-ee: Detector background

- Synchrotron radiation, beam-gas, Touschek scattering, radiative Bhabha, thermal photons are on the extension of what experienced at LEP, PEP-II, KEKB, etc.
- Beamstrahlung is new for a circular collider, and expected to generate a wider, non-Gaussian beam energy distribution. However it has been estimated that it results in no average ECM shift (see the backup), and that it is not very serious for the detector background.



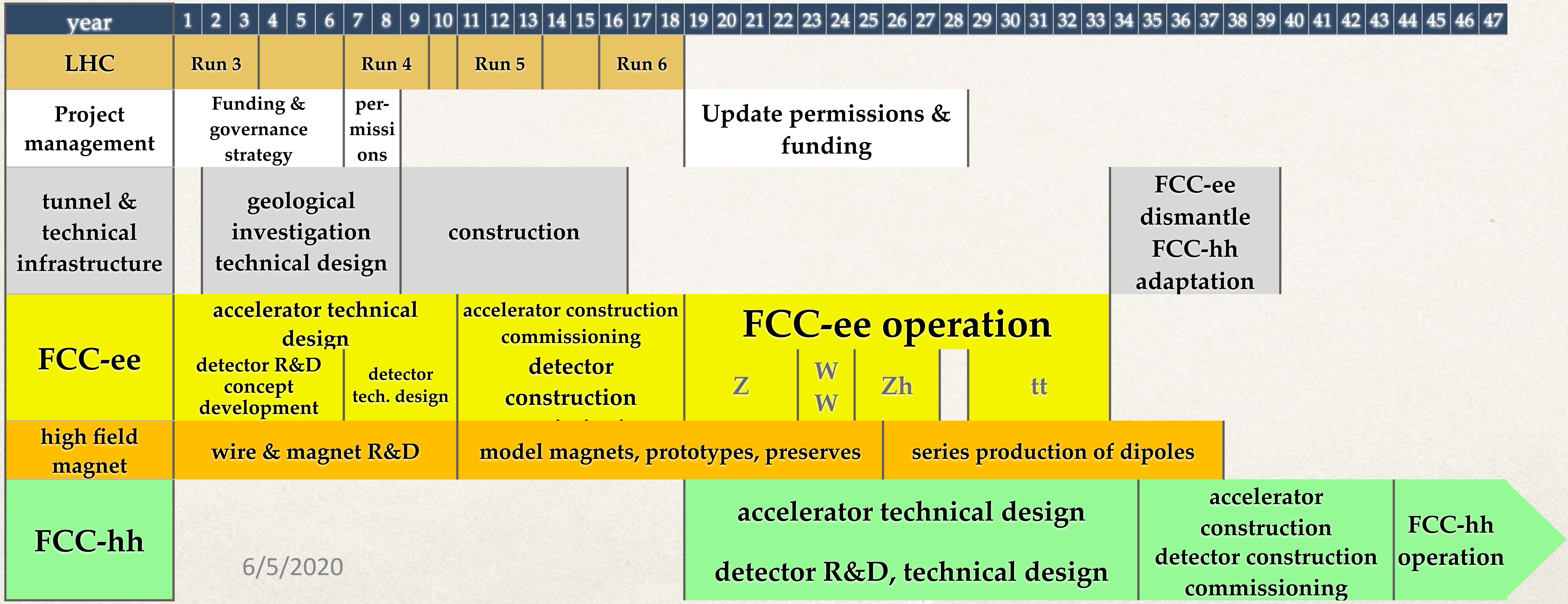


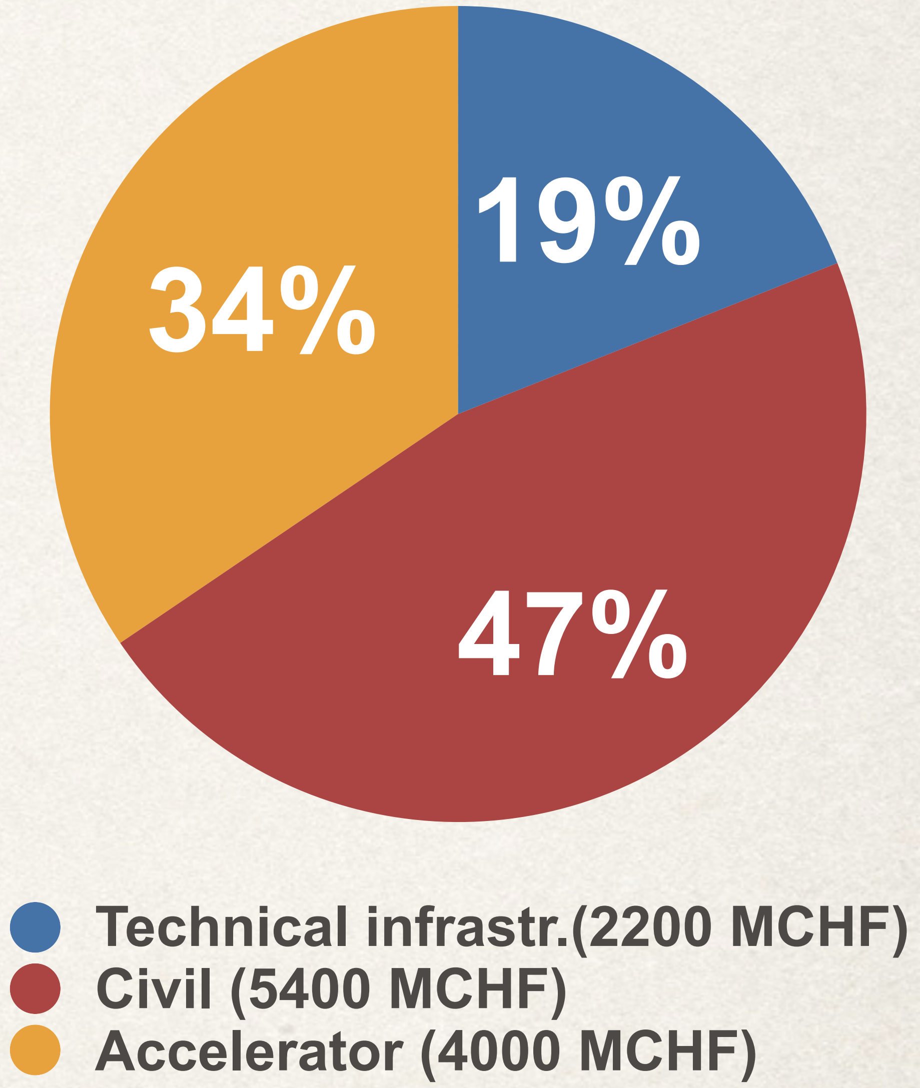
D. Shatilov

- Pair production is unexperienced (as in any colliders), but estimated less serious.
- Challenges are in the detailed mechanical design of detector/accelerator components including precise alignment, magnetic field including detector & compensating solenoids, heating by HOM and SR, electromagnetic forces, vibration, vacuum, assembling procedure, etc.

FCC-ee: Technology, cost, schedule

- Technologies are basically experienced and matured.
  - Some R&Ds are on-going for NbCu RF cavities, high-efficiency RF sources, machine detector interface, beam energy, luminosity & polarization measurements & handling, online operation software, etc.
- Detailed engineering needs 5 years from now to finalize.
- Commissioning assumes a startup run for 2 years at Z.
- One-year break before $t\bar{t}$ operation to install additional RF systems.
- The cost of accelerator is only 34% of the total cost. The most of civil and TI are reused for FCC-hh.



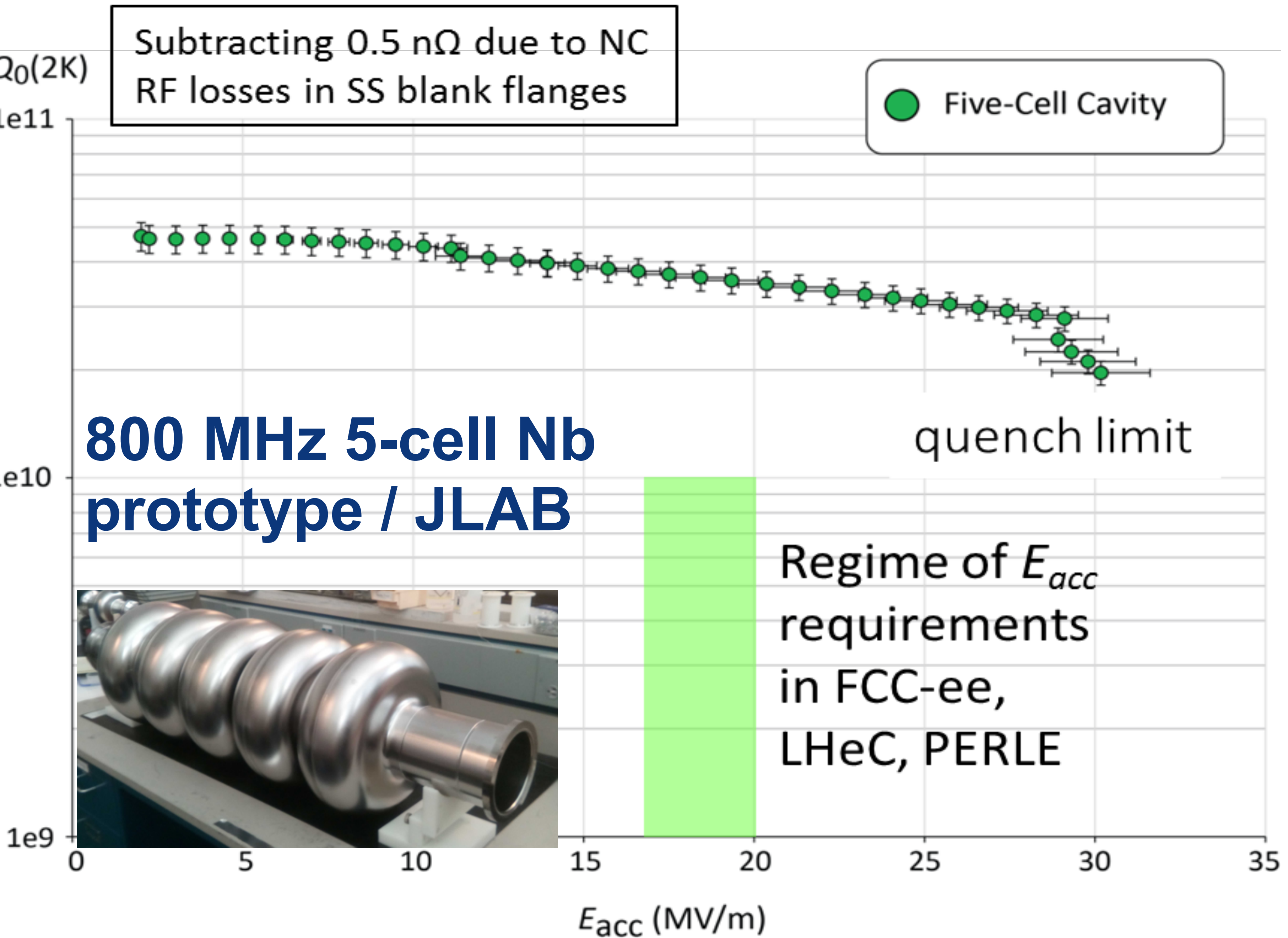


FCC-ee R&D: RF, cryo-modules, power sources

R&D aimed at improving performance & efficiency and reducing cost:

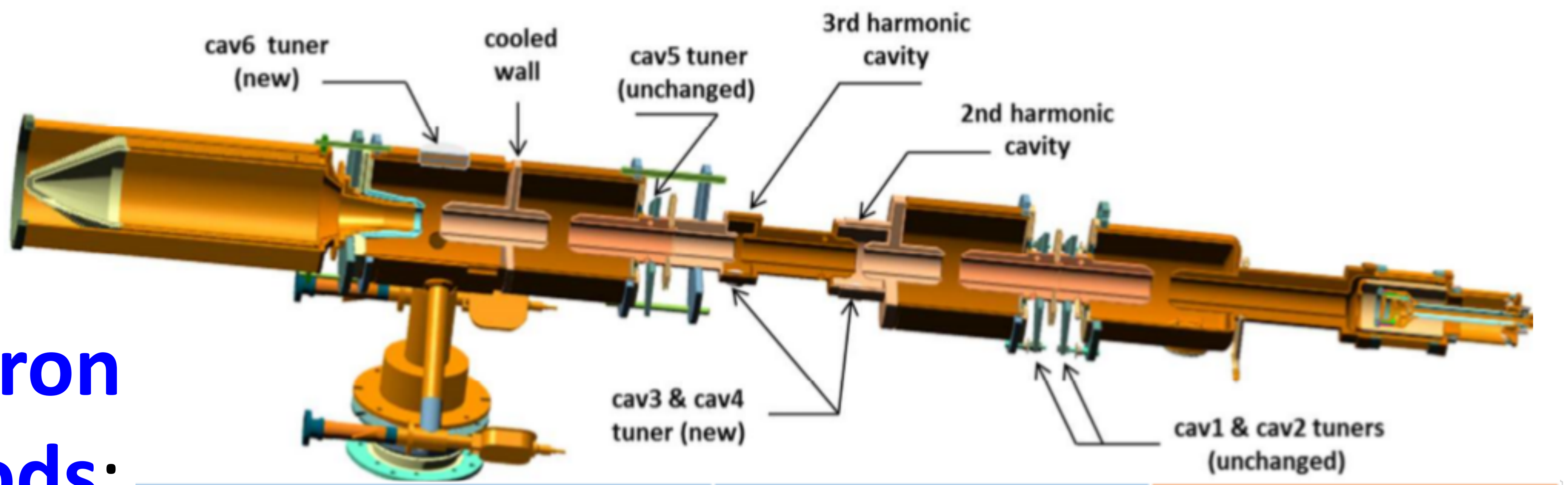
- improved Nb/Cu coating/sputtering (e.g. ECR fibre growth, HiPIMS)
- new cavity fabrication techniques (e.g. EHF, improved polishing, seamless…)
- coating of A15 superconductors (e.g. Nb_3Sn), · cryo-module design optimisation
- bulk Nb cavity R&D at FNAL, JLAB, Cornell, also KEK and CEPC/IHEP
- MW-class fundamental power couplers for 400 MHz; · novel high-efficiency klystrons

prototype FCC SRF cavities at JLAB



Jefferson Lab

high-efficiency klystron at CERN



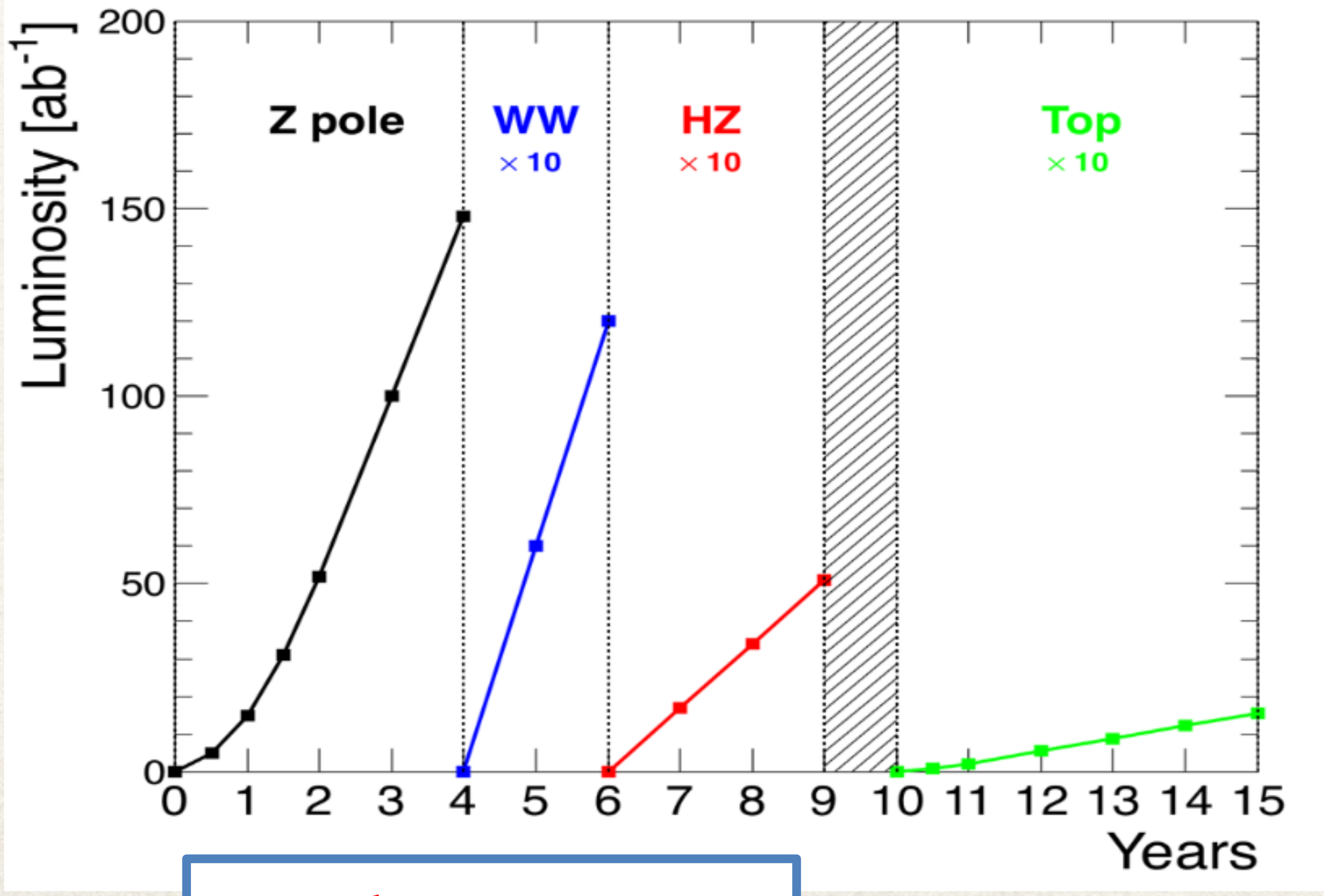
New klystron bunching methods: **LHC klystron retrofit** as proof of principle for FCC

Parameter	present TH2167	CSM upgrade
Frequency [MHz]	400	
Beam voltage [kV]	54	
Saturated RF power [kW]	**300**	**350**
Efficiency [%]	**60**	**70**

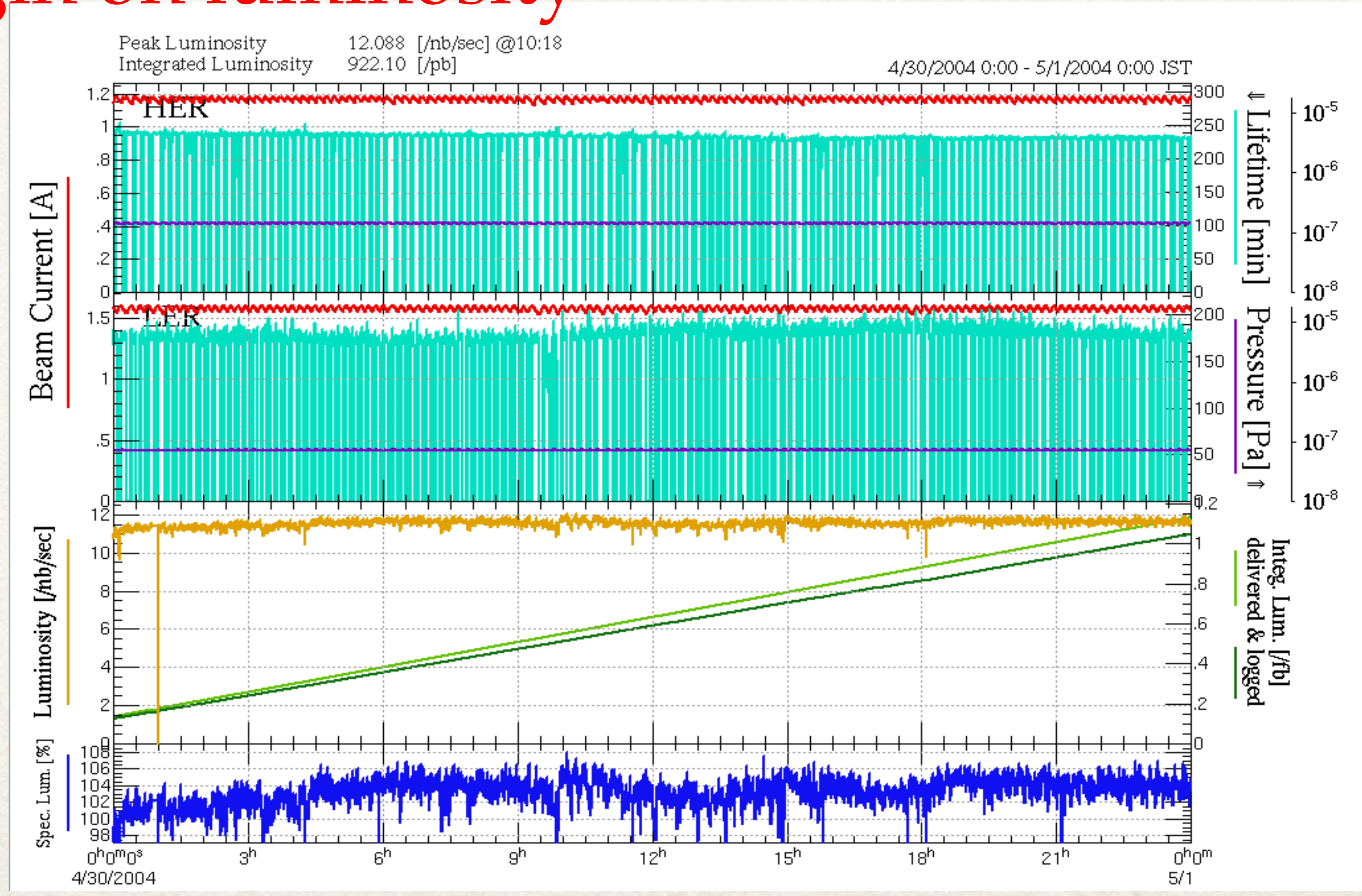
FCC-ee: operation model

Working point	Z, years 1-2	Z, later	WW	HZ	tt threshold and above	
√s (GeV)	88, 91, 94		157, 163	240	340 – 350	365
√s precision (MeV)	<0.1		0.3	1	2	
Lumi/IP (10^{34} cm^{-2}s^{-1})	115	230	28	8.5	0.95	1.55
Lumi/year (2 IP, ab^{-1})	24	48	6	1.7	0.2	0.34
Physics goal (ab^{-1})	150 ab-1 (30,90,30 ab^{-1})		10 ab^{-1}	5 ab^{-1}	0.2 ab^{-1}	1.5 ab^{-1}
Run time (year)	2	2	2	3	1	4
Number of events	5×10^{12} Z		10^8 W^+W	10^6 HZ 25k WW→ H	10^6 tt 200k HZ 50k WW→ H	

- 185 physics days / year, 75% efficiency, -10% margin on luminosity



Total : 15 years



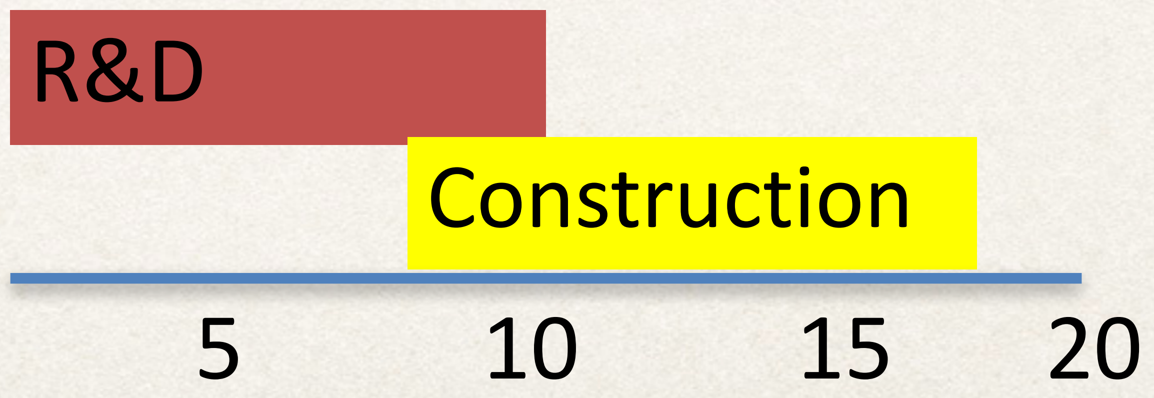
KEKB has demonstrated a very high efficiency >80% with top-up (continuous) injection

FCC-ee: Technical Maturity

- Overall Technical Maturity: 2– Some R&D in a few key areas required

- Critical Technologies and TRL level:
  - High efficiency & high performance RF system.
    - 400 MHz NbCu cavity, RF system (TRL 7)
    - 800 MHz Nb cavity, RF system (TRL 8)
    - High efficiency klystrons (TRL 4-7)
  - Machine-detector interface components with precise alignment & assembly (TRL 6).
  - Beam diagnostics and handling for low-emittance, high luminosity collision with beamstrahlung (TRL 6).

- Technically limited timeline (see slide 9)



Thank you!

From beam energy to E_{CM}

$$\sqrt{s} = 2\sqrt{E_b^+ E_b^-}\cos\alpha/2 \approx E^+_b + E^-_b$$

Energy gain (RF) = losses in the storage ring
Synchrotron radiation (SR)
beamstrahlung (BS)

$$\boxed{\Delta_{RF} = 2\Delta_{SRi} + 2\Delta_{SRe} + 2\Delta_{BS}}$$

at the Z (O of mag.):

$\Delta_{SR} = 2\Delta_{SRi} + 2\Delta_{SRe}$ =36 MeV

$\Delta_{SRe} - \Delta_{SRi} \approx \alpha/2\pi\ \Delta_{SR}$ = 0.17 MeV

Δ_{BS} = 0 up to 0.62 MeV

the average energies E_0 around the ring
are determined by the magnetic fields
➔same for colliding or non-colliding beams
-- measured by resonant depolarization
-- can be different for e^+ and e^-